IBIS-AMI Modeling and Simulation of DMT in Preparation for 448Gbps Applications

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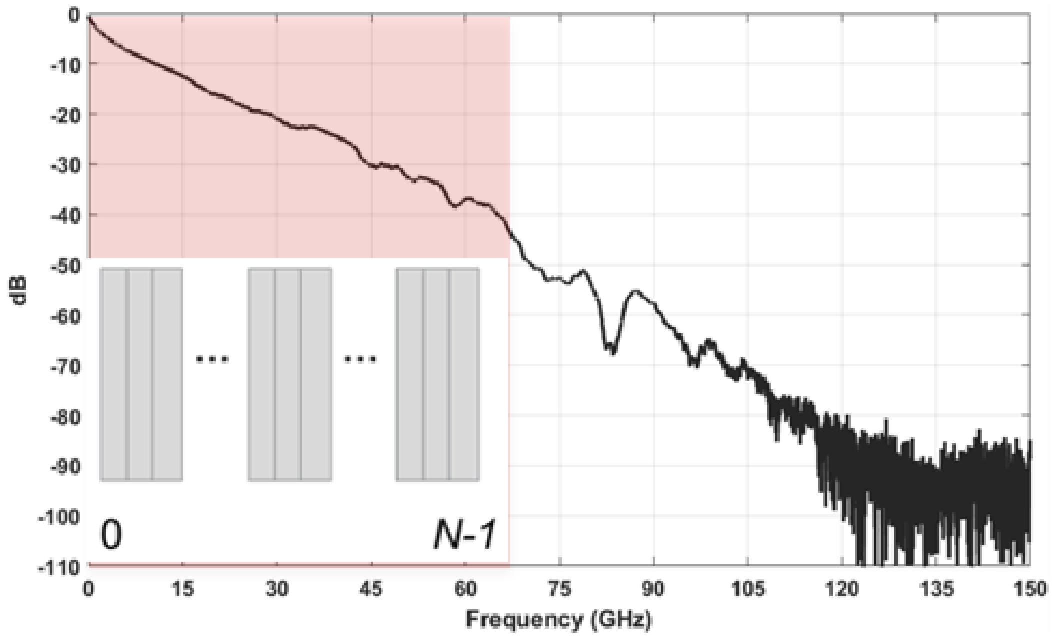
Introduction

- Unlike PAM signaling, DMT (discrete multi-tone) divides the baseband channel into multiple sub-channels
- Now, each sub-channel can carry different number of bits based on the robustness of the sub-channel



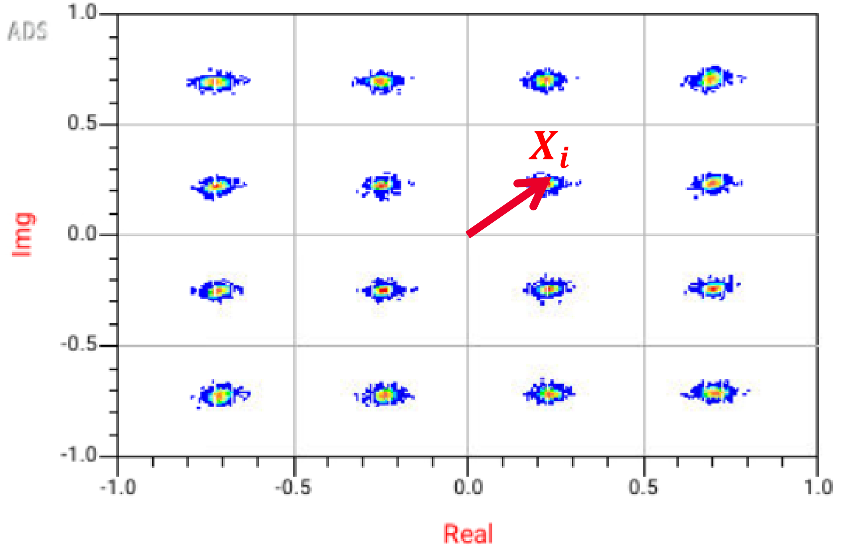
- The focus of this presentation is to introduce IBIS-AMI modeling for link channels using DMT

Review of QAM (Quadrature Amplitude Modulation)

- QAM-N signal ($N = 2^M$)

$$\boldsymbol{S(t) = Re\left[X_i \cdot e^{j2\pi f_c t}\right] = Re[X_i] \cdot cos(2\pi f_c t) - Im[X_i] \cdot sin(2\pi f_c t) = I(t) + Q(t), \qquad i = 1, \ldots, N}$$

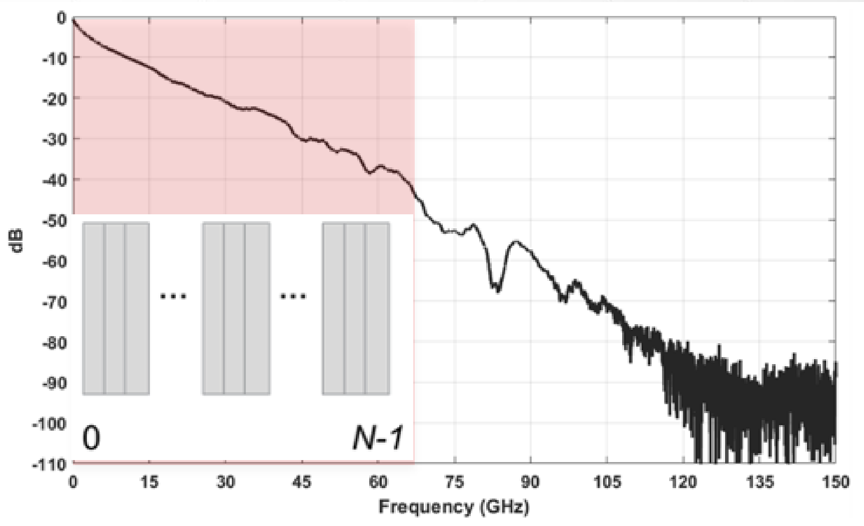
- TX maps each M-bit sequence to a unique complex amplitude $\boldsymbol{X_i}$ (QAM symbol) and modulates $\boldsymbol{I}$ and $\boldsymbol{Q}$ signals with $\boldsymbol{X_i}$
- RX recovers $\boldsymbol{X_i}$ from $\boldsymbol{I}$ and $\boldsymbol{Q}$ amplitudes and maps $\boldsymbol{X_i}$ to the M-bit sequence
- Each QAM symbol carries M bits

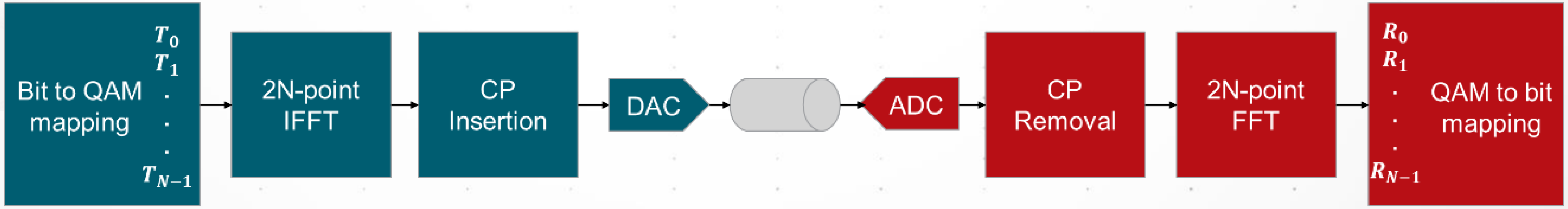


QAM16 example: each QAM16 symbol represents a 4-bit sequence

Key Components in DMT

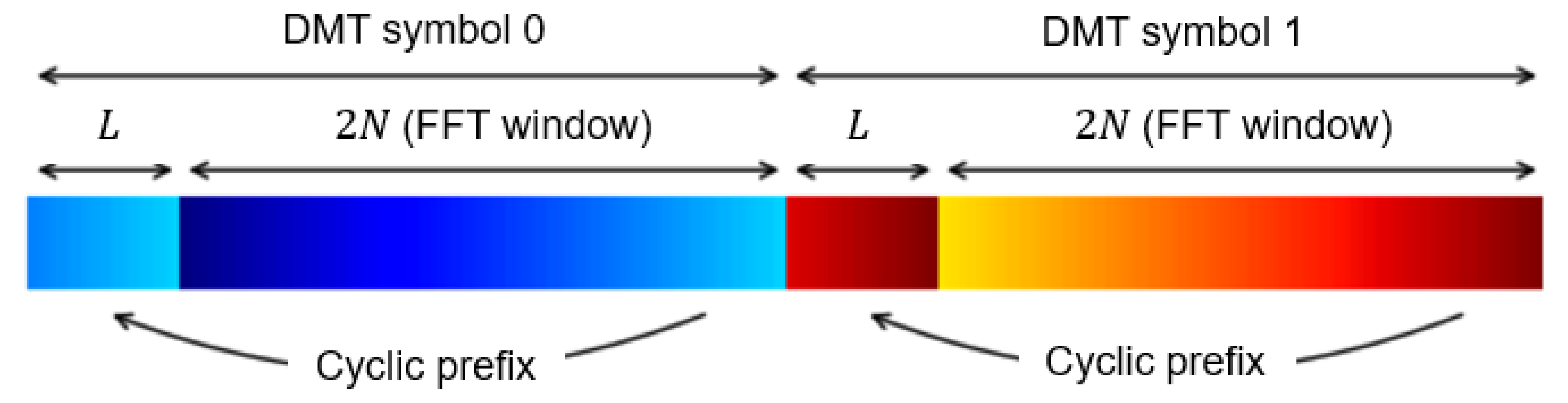
1. Divide the channel into N sub-channels, from DC to fmax
2. Assign modulation order to each sub-channel, $QAM(k)$
   - For a given time frame, generate the complex values, $T_0, T_1, \dots T_{N-1}$
3. Extend to the negative frequency to form $2N$-point complex array
4. Do $2N$-point IFFT to produce a valued array: $d_0, d_1, \dots, d_{2N-1}$
5. Insert CP of length L: $d_{2N-L}, \dots, d_{2N-1}, d_0, d_1, \dots, d_{2N-1}$
6. Transmit the $2N + L$ samples
7. Remove the first L symbols from the received symbols
8. Apply $2N$-point FFT the remaining to obtain $R_0, R_1, \dots, R_{2N-1}$
9. Detect and map R_k back to binary data





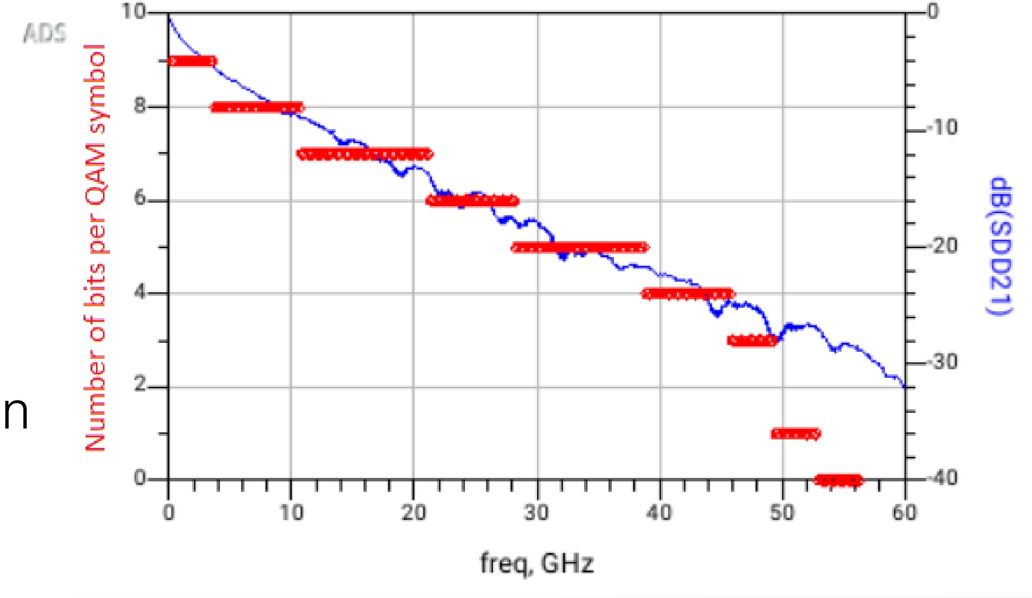
Cyclic Prefix (CP) and Why

- Recall that
  - Multiplication in the frequency domain corresponds to circular convolution in the time domain; likewise, circular convolution in the time domain corresponds to multiplication in the frequency domain
  - The channel impact on the transmitted signal can be presented as a linear convolution of the channel impulse response with the transmitted signal
- Therefore, we would need some way of turning the channel response into a circular convolution, not a linear convolution. This is how we can do it:
  - For each time-domain block generated by the transmitter, a CP is inserted before it. The CP takes the last L samples of the $2N$-sample time-domain symbol and concatenates it to the front of the block to be transmitted



DMT Advantages

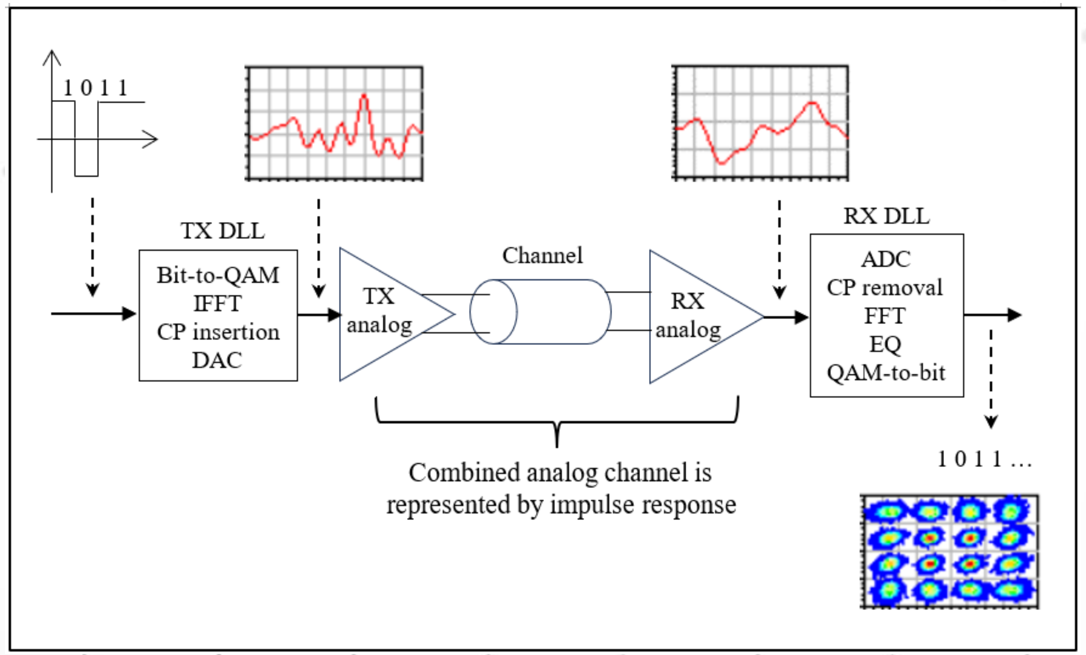
- Bit loading
  - Assign different numbers of bits to different sub-channels
  - The higher the sub-channel SNR, the more bits are assigned to it
  - Maximized bandwidth efficiency
  - Tolerant of channel spectral notch/discontinuity
- RX equalization
  - CP renders the channel effect a circular convolution
  - Each sub-channel is a narrow band signal
  - RX equalization is as simple as a scalar multiplication in frequency domain



AMI Modeling for DMT Proposal (1)

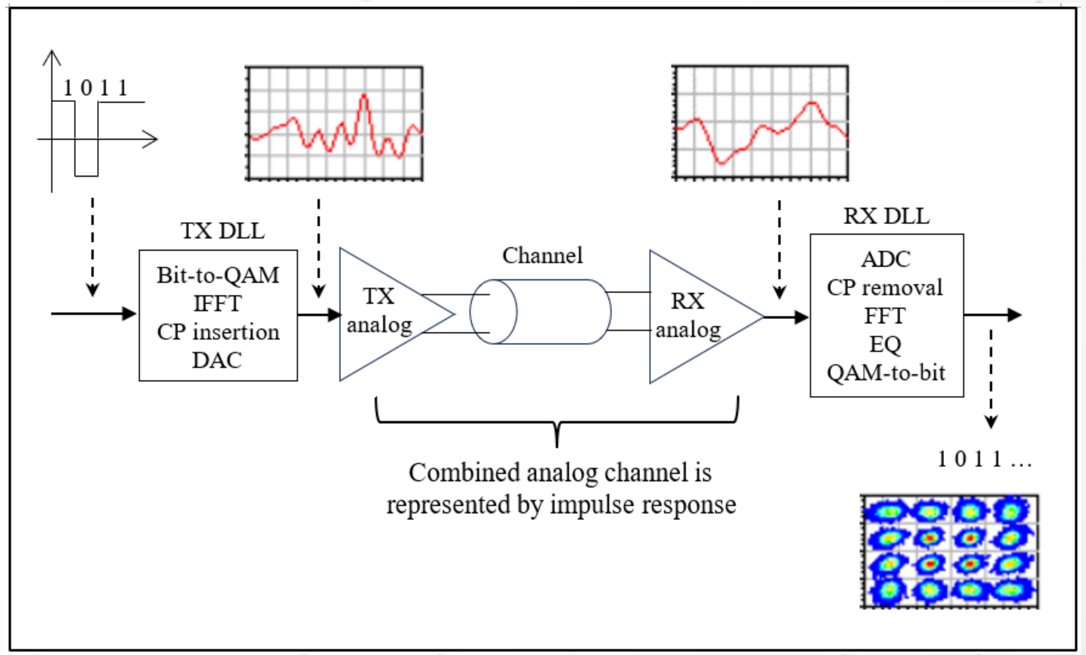
- TX DLL encapsulates
  - sample rate and sub-channel number determinations
  - bit loading
  - bit-to-QAM mapping
  - IFFT
  - CP insertion
  - DAC
  - TX front-end

- RX DLL encapsulates
  - timing synchronization
  - ADC
  - CP removal
  - FFT
  - Equalization
  - QAM-to-bit mapping
  - bit data recovery



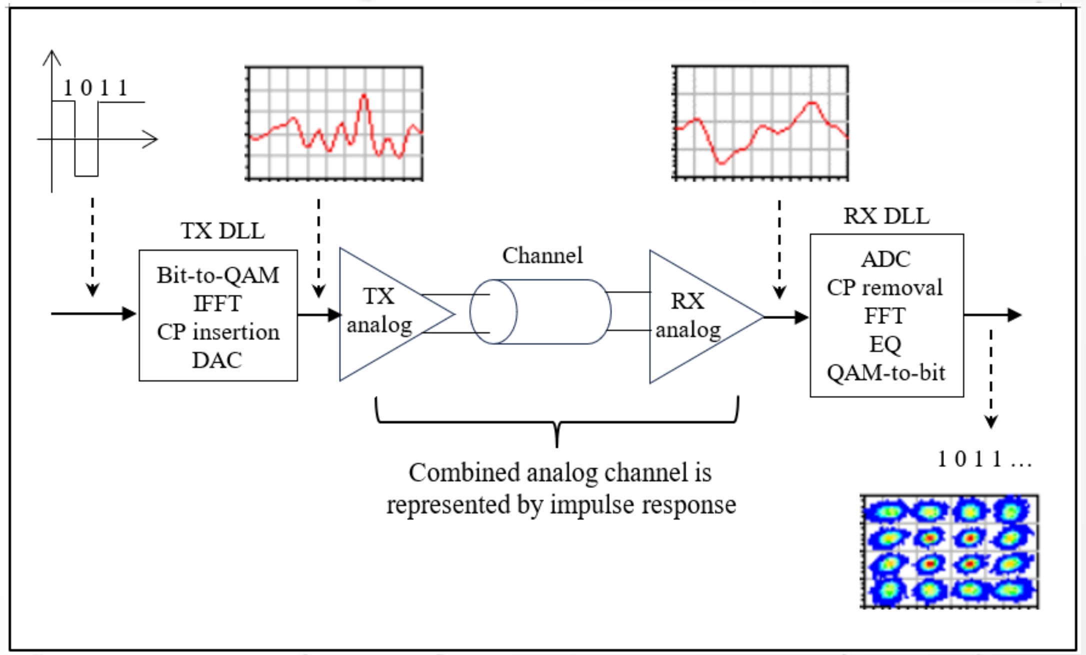
AMI Modeling for DMT Proposal (2)

- TX AMI_Init
  - Use the inverse of the target data rate for the symbol_time argument
  - Based on the data rate and the input impulse response of the analog channel, TX AMI_Init determines configurations such as sample rate, sub-channel number, bit loading, CP length, etc.
  - TX AMI_Init writes the configuration data to a file to be read by the RX AMI_Init
  - To distinguish files used by different TX-RX pairs, the file name can be passed into TX and RX DLLs by a Model Specific parameter of Usage “In” and Type “String”
  - EDA tool or model user is responsible for assigning the same file name to pairing TX and RX models



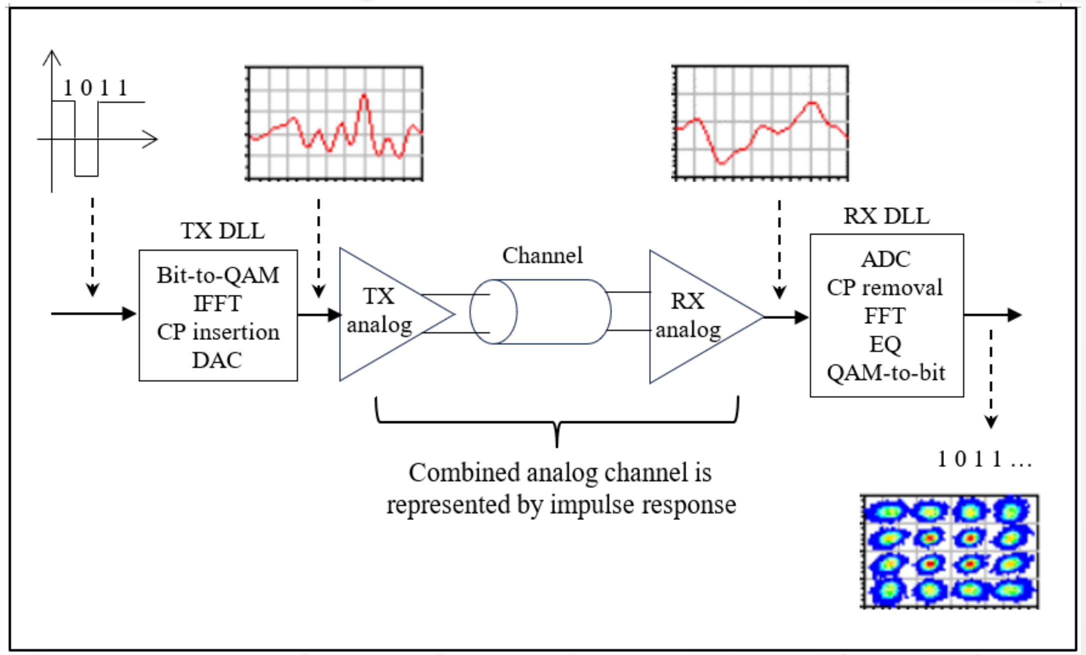
AMI Modeling for DMT Proposal (3)

- RX AMI_Init
  - RX AMI_Init reads the file and retrieves the TX configuration
  - Model developer is responsible for model interoperability when TX and RX exchange DMT configuration data through the file
  - Model developer is also responsible for the consistency between TX bit-to-QAM mapping and RX QAM-to-bit mapping
  - As in TX AMI_Init, use the inverse of the target data rate for the symbol_time argument in RX AMI_Init



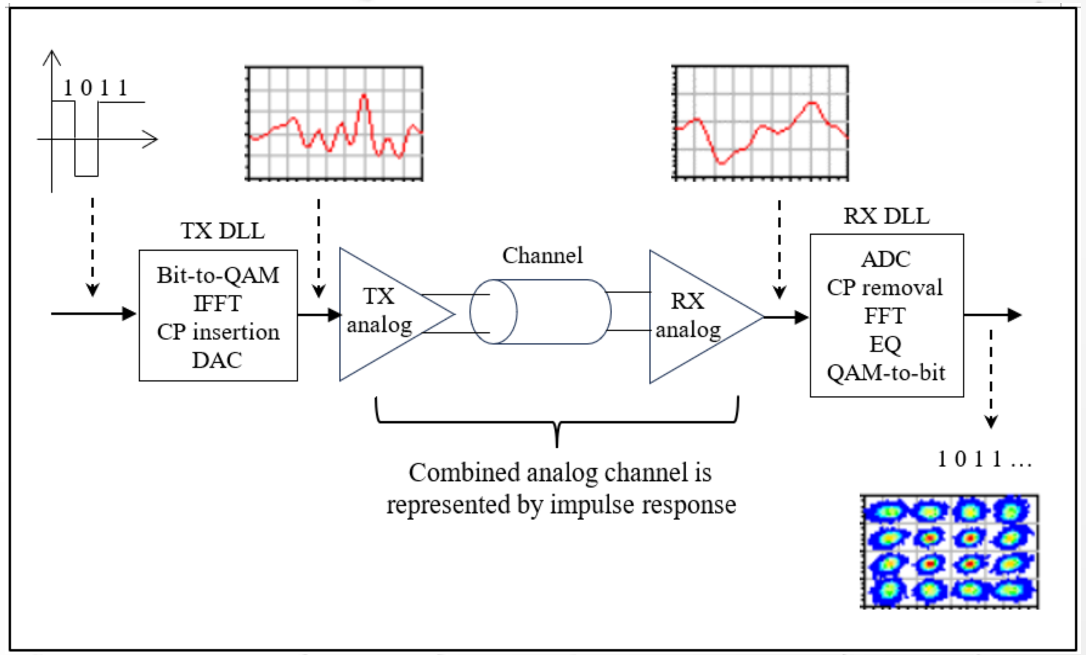
AMI Modeling for DMT Proposal (4)

- Another possible mechanism for exchanging configuration information between TX and RX
  - TX AMI_Init writes the configuration data to a new Reserved parameter and returns it in the AMI_parameters_out output string
  - EDA tool extracts the parameter value and includes it in the AMI_parameters_in input string of RX AMI_Init
  - The parameter is of Usage “InOut” and Type “String”
  - The string content and format of this parameter is proprietary between TX and RX models
- Both approaches provide the same flexibility for model development (the file approach is used in this paper)



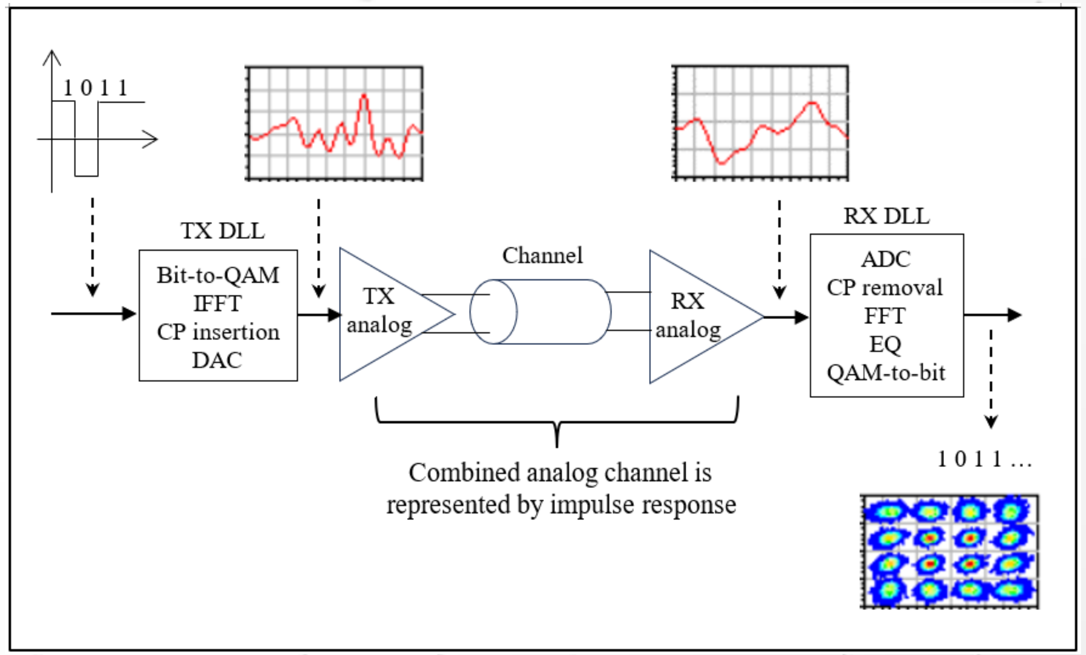
AMI Modeling for DMT Proposal (5)

- TX AMI_GetWave
  - The input waveform is a binary waveform at the target data rate generated by the simulator
  - TX AMI_GetWave performs bit-to-QAM conversion, IFFT, CP insertion and DAC and returns the DMT symbol (including CP) waveform
  - TX jitters, if present, need to be injected by TX AMI_GetWave, and the input waveform should be free of jitter
  - The AMI_GetWave block size is not required to be a multiple of the DMT symbol (including CP) length



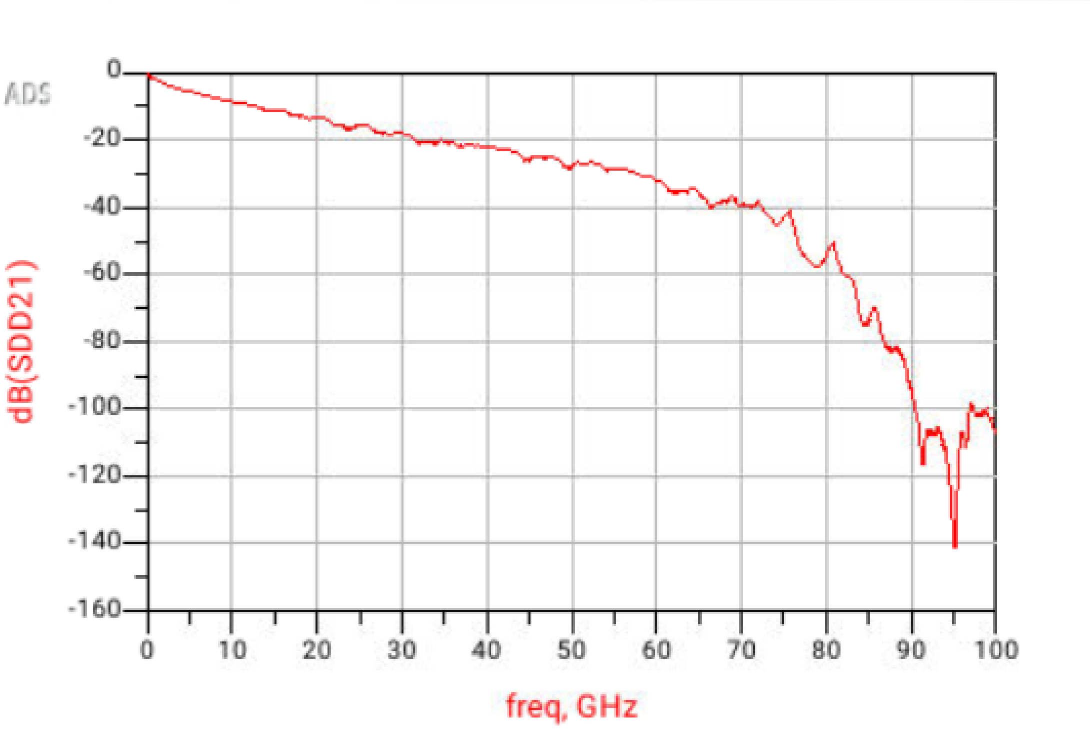
AMI Modeling for DMT Proposal (6)

- RX AMI_GetWave
  - performs timing synchronization, ADC, CP removal, FFT, equalization, QAM-to-bit mapping, and bit data recovery
  - returns recovered bits through a new AMI Reserved parameter of Type “String” and Usage “Out” for the simulator to calculate BER and effective data rate
  - can also return recovered QAM constellations through another new AMI Reserved parameter of Type “String” and Usage “Out” for post-processing such as constellation diagram generation



DMT AMI Simulation Examples

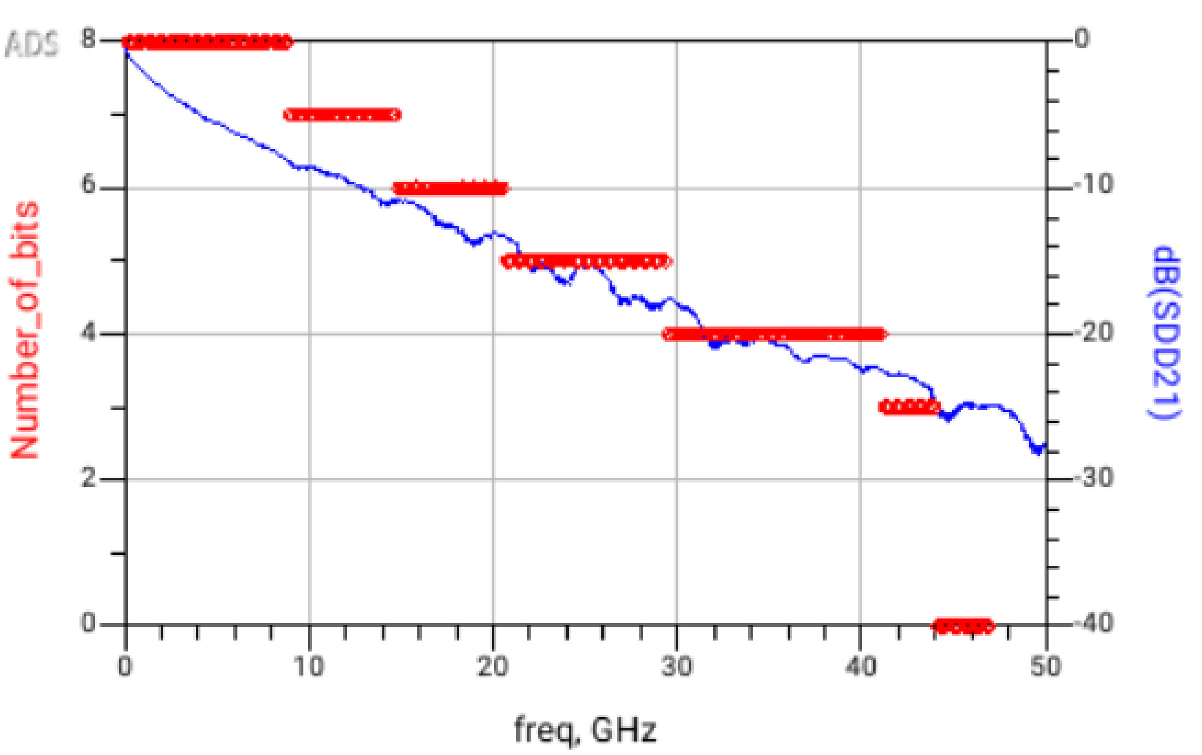
- Target data rate: 200 and 240 Gbps for 100 and 120 GHz sample rates, respectively
- 26 dB differential insertion loss at 50 GHz
- 16 frequency bands with 15 sub-channels per band
- Number of sub-channels: 16*15=240
- Same QAM order for all 15 sub-channels in each band
- FFT size: 512 (16 unused FFT frequencies including DC)
- CP length: 64 (12.5% of FFT size)
- TX model
  - 9-bit DAC with a full swing of 1 Vdpp
- RX model
  - 8-bit ADC
  - Applies AWGN (additive white Gaussian noise) at RX input before AGC
  - Noise RMS: 2.5 and 2 mV at 100 and 120 GHz sample rates, respectively



Results of 100 GHz Sample Rate (1)

- QAM order setting for frequency bands

Bands	1-3	4, 5	6, 7	8-10	11-14	15	16
Number of bits per QAM symbol	8	7	6	5	4	3	0

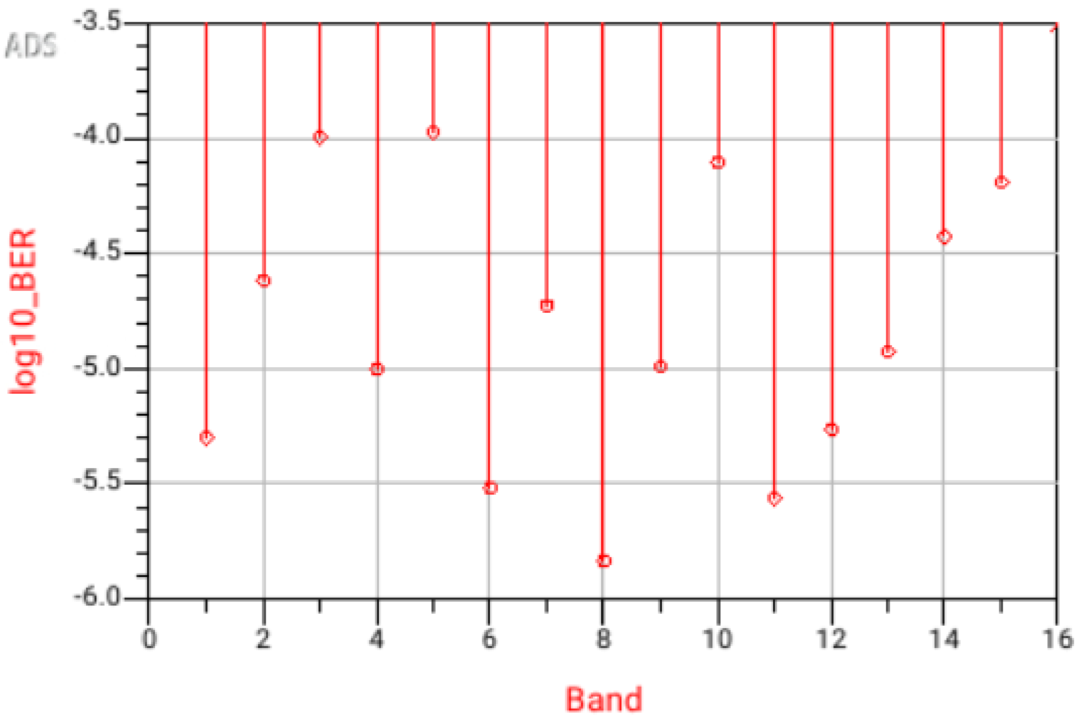


* Band 16 is not used

Results of 100 GHz Sample Rate (2)

- Actual date rate achieved: 200.08 Gbps
- Overall BER: 3.42×10^{-5}

BER in individual band



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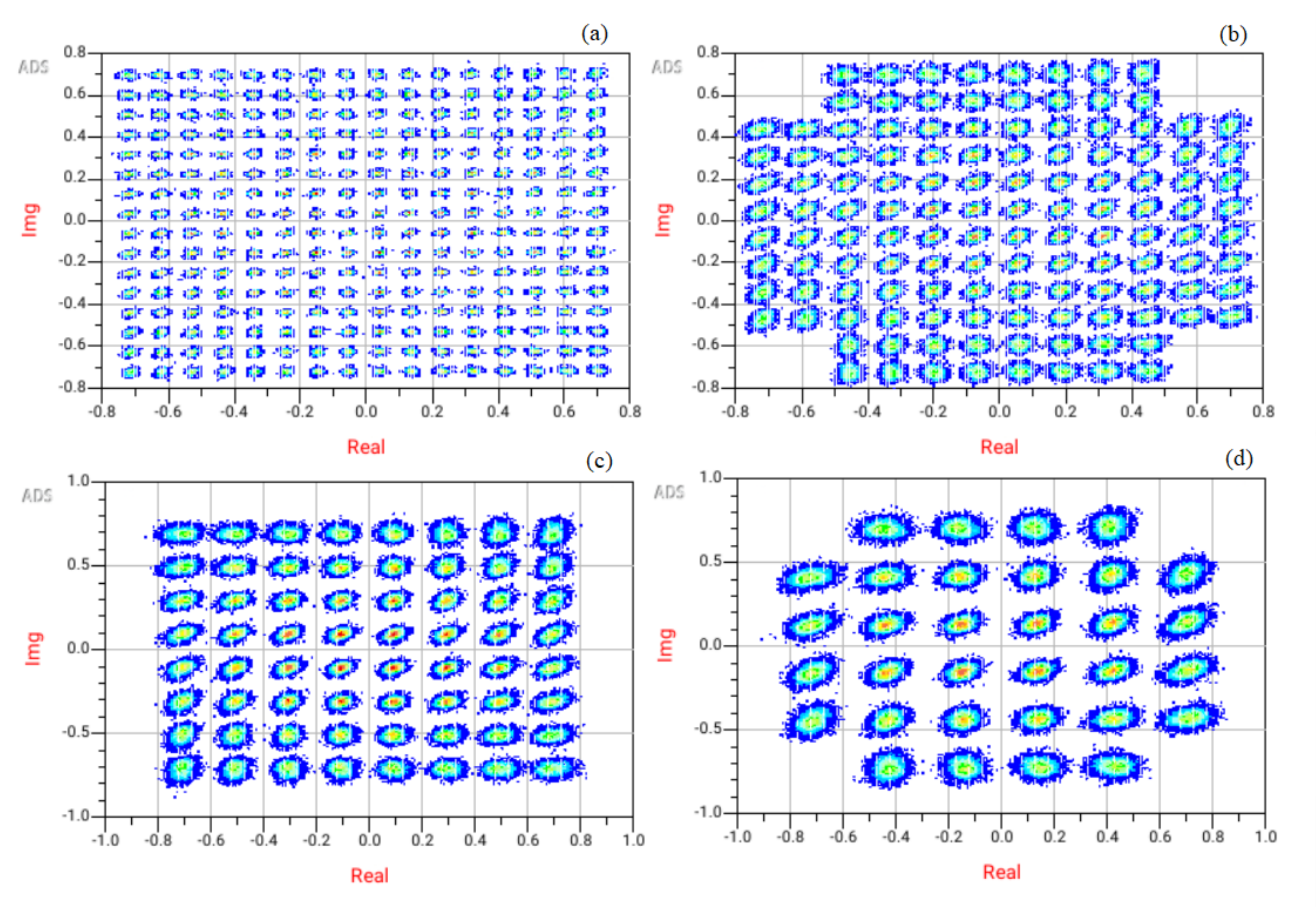
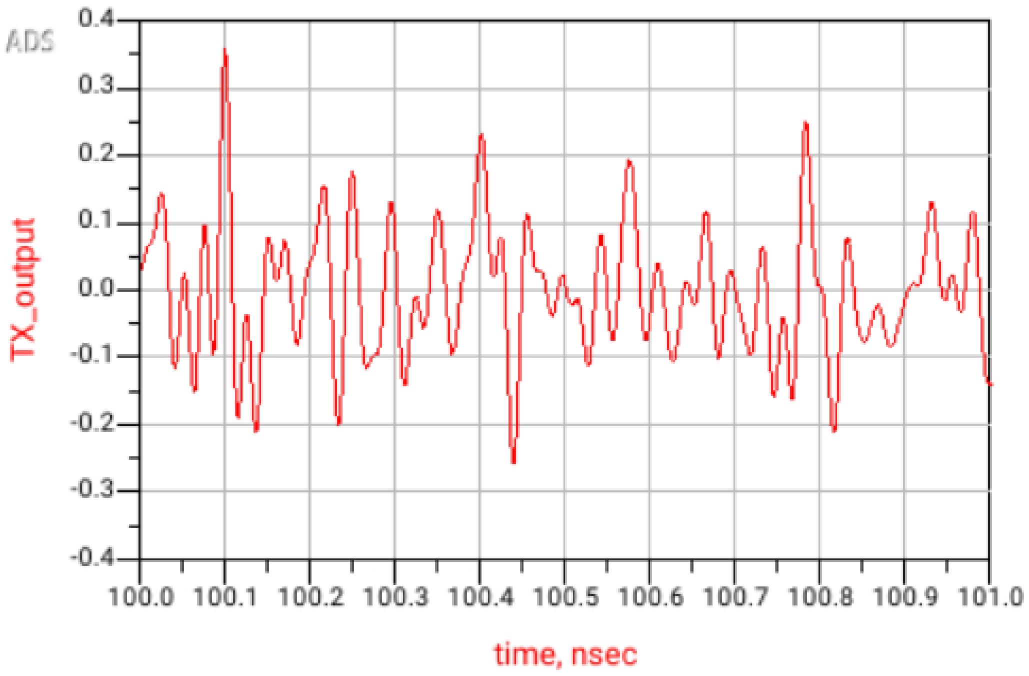
Results of 100 GHz Sample Rate (3)

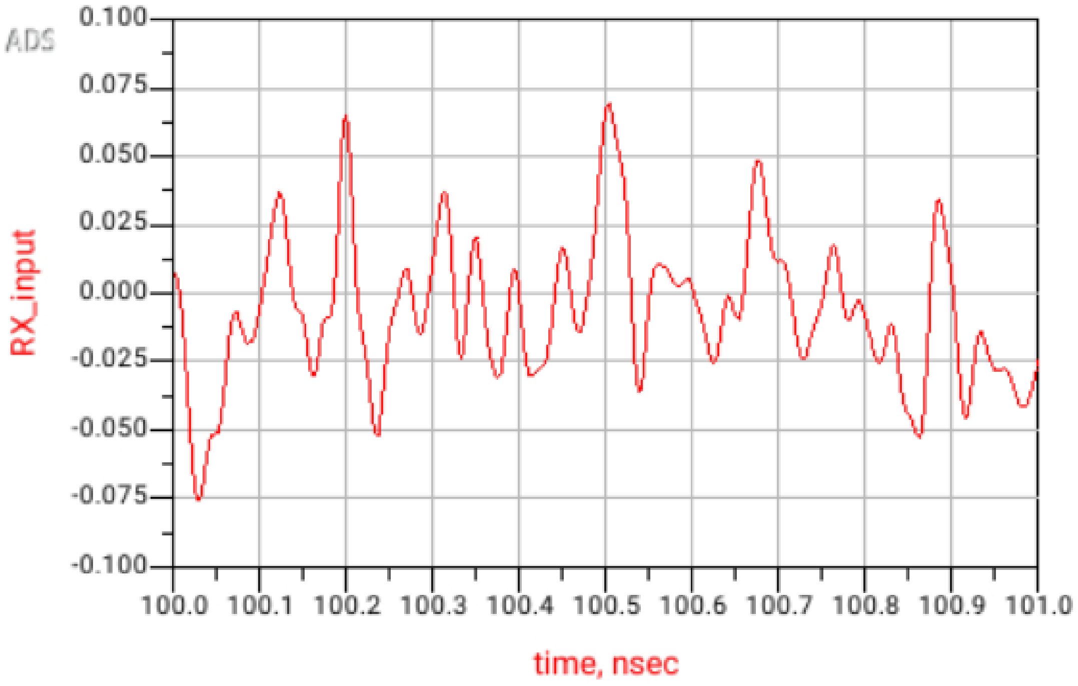
- Constellation diagrams of (a) Band 1, (b) Band 5, (c) Band 7, and (d) Band 9



Results of 100 GHz Sample Rate (4)

- Waveforms of TX output and RX input

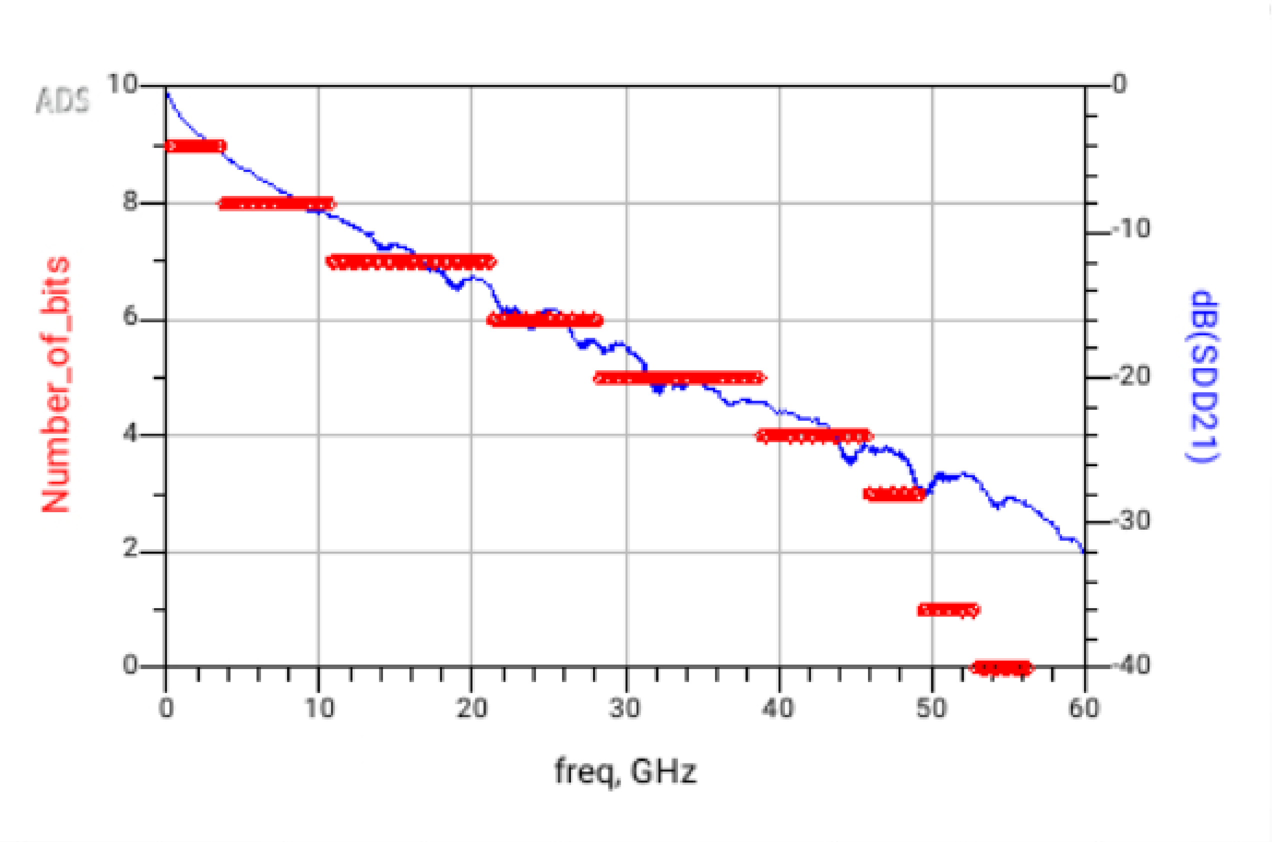




Results of 120 GHz Sample Rate (1)

- QAM order setting for frequency bands

Band	1	2, 3	4-6	7, 8	9-11	12, 13	14	15	16
Number of bits per QAM symbol	9	8	7	6	5	4	3	1	0

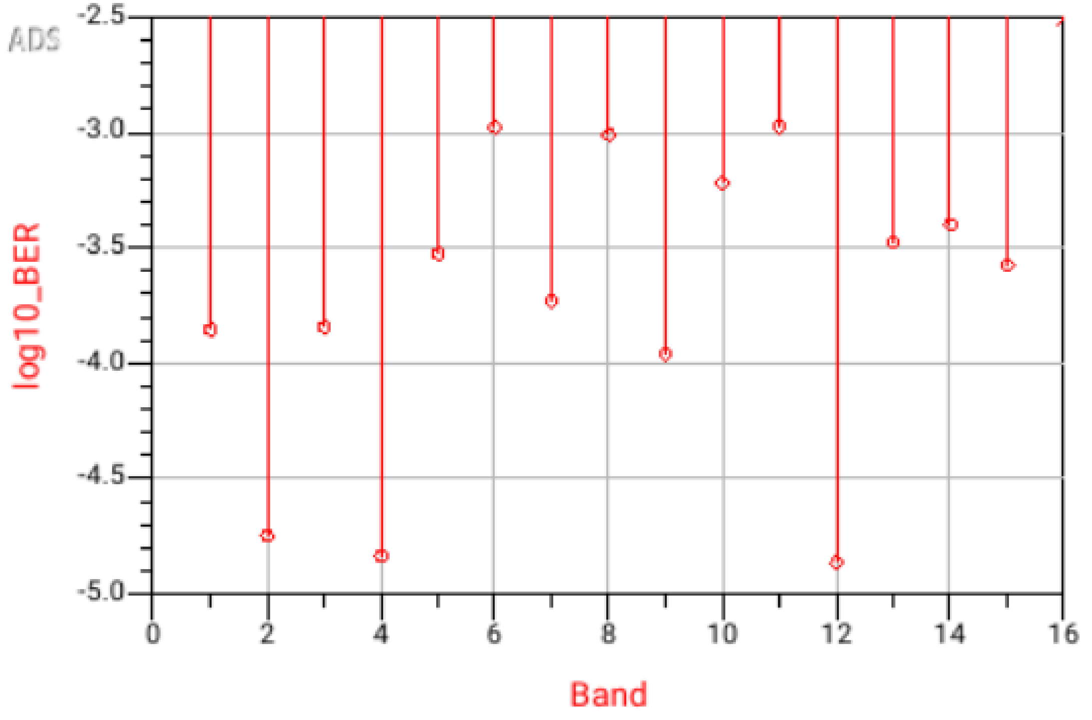


* Band 16 is not used

Results of 120 GHz Sample Rate (2)

- Actual date rate achieved: 242.96 Gbps
- Overall BER: $3.64x10^{-4}$

BER in individual band



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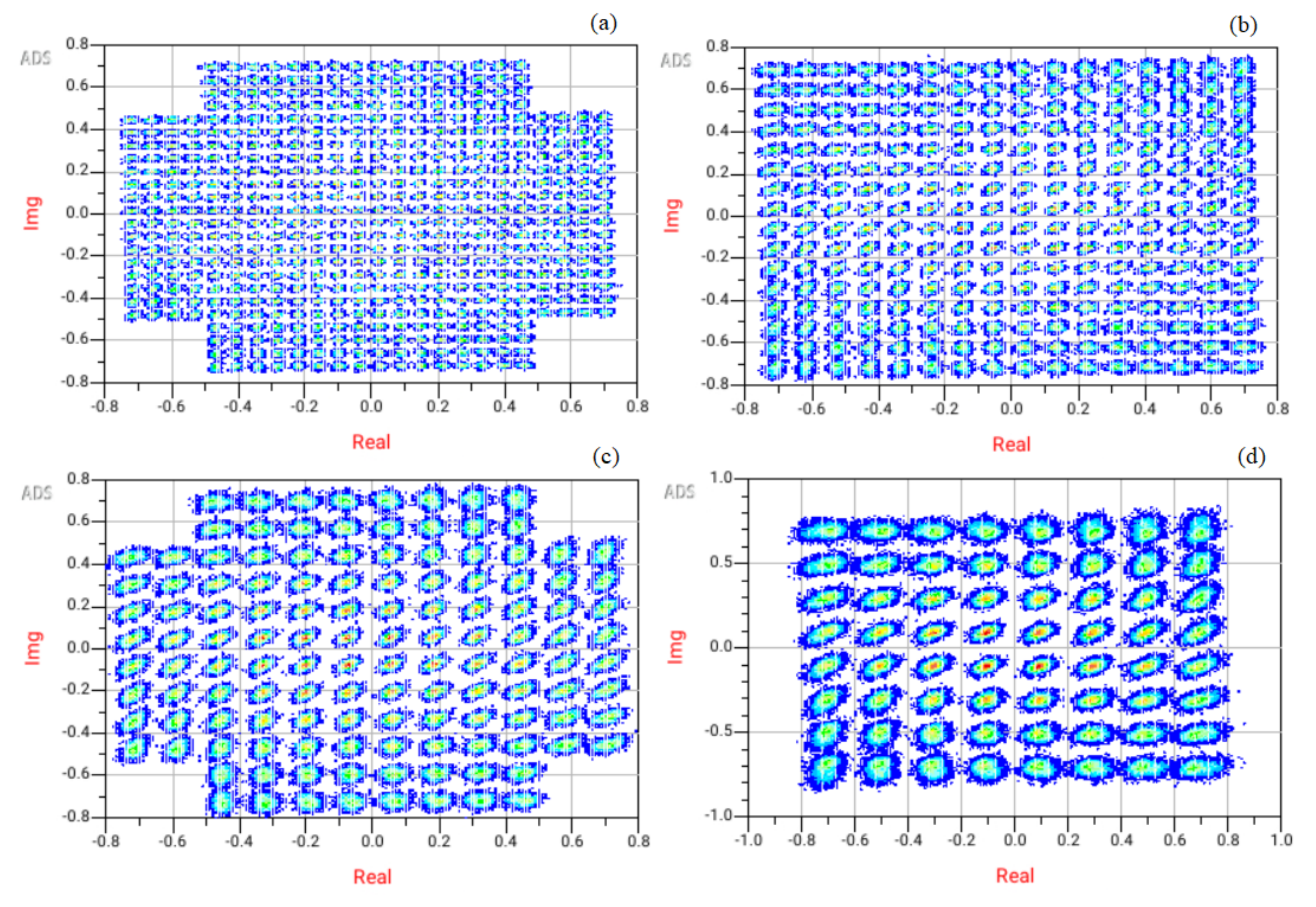
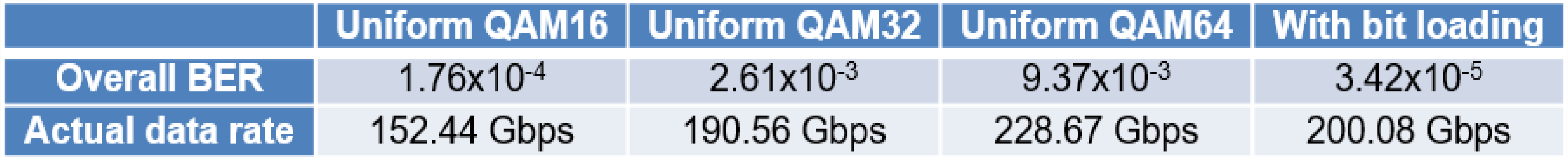
Results of 120 GHz Sample Rate (3)

- Constellation diagrams of (a) Band 1, (b) Band 3, (c) Band 5, and (d) Band 7



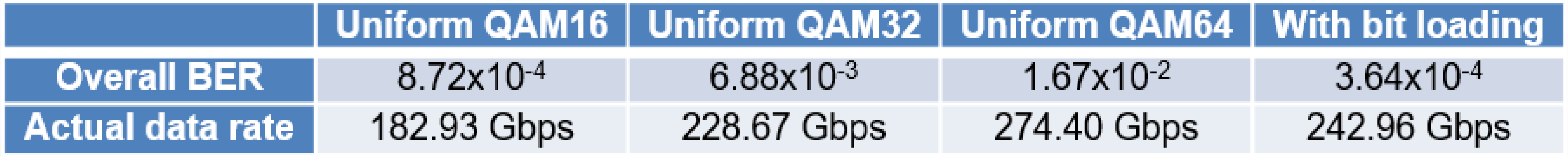
Results of Uniform QAM Modulation (1)

- Uniform QAM order across all 240 sub-channels
- QAM16, QAM32 and QAM64 are studied
- 100 GHz sample rate:



	Uniform QAM16	Uniform QAM32	Uniform QAM64	With bit loading
Overall BER	1.76×10^{-4}	2.61×10^{-3}	9.37×10^{-3}	3.42×10^{-5}
Actual data rate	152.44 Gbps	190.56 Gbps	228.67 Gbps	200.08 Gbps

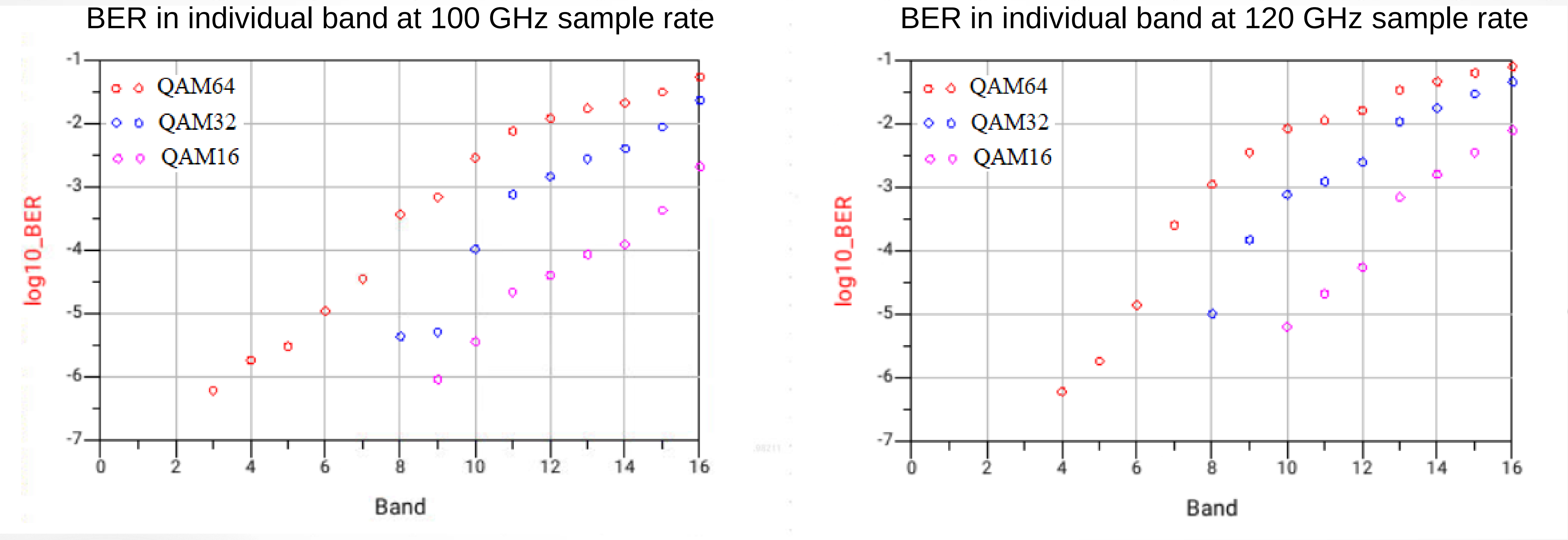
- 120 GHz sample rate:



	Uniform QAM16	Uniform QAM32	Uniform QAM64	With bit loading
Overall BER	8.72×10^{-4}	6.88×10^{-3}	1.67×10^{-2}	3.64×10^{-4}
Actual data rate	182.93 Gbps	228.67 Gbps	274.40 Gbps	242.96 Gbps

- At both sample rates, uniform QAM yields worse BER than bit loading does
- The higher the QAM order, the worse the BER

Results of Uniform QAM Modulation (2)



- The higher the sub-channel frequency, the higher the channel loss, the lower the SNR, the worse the BER in the frequency band

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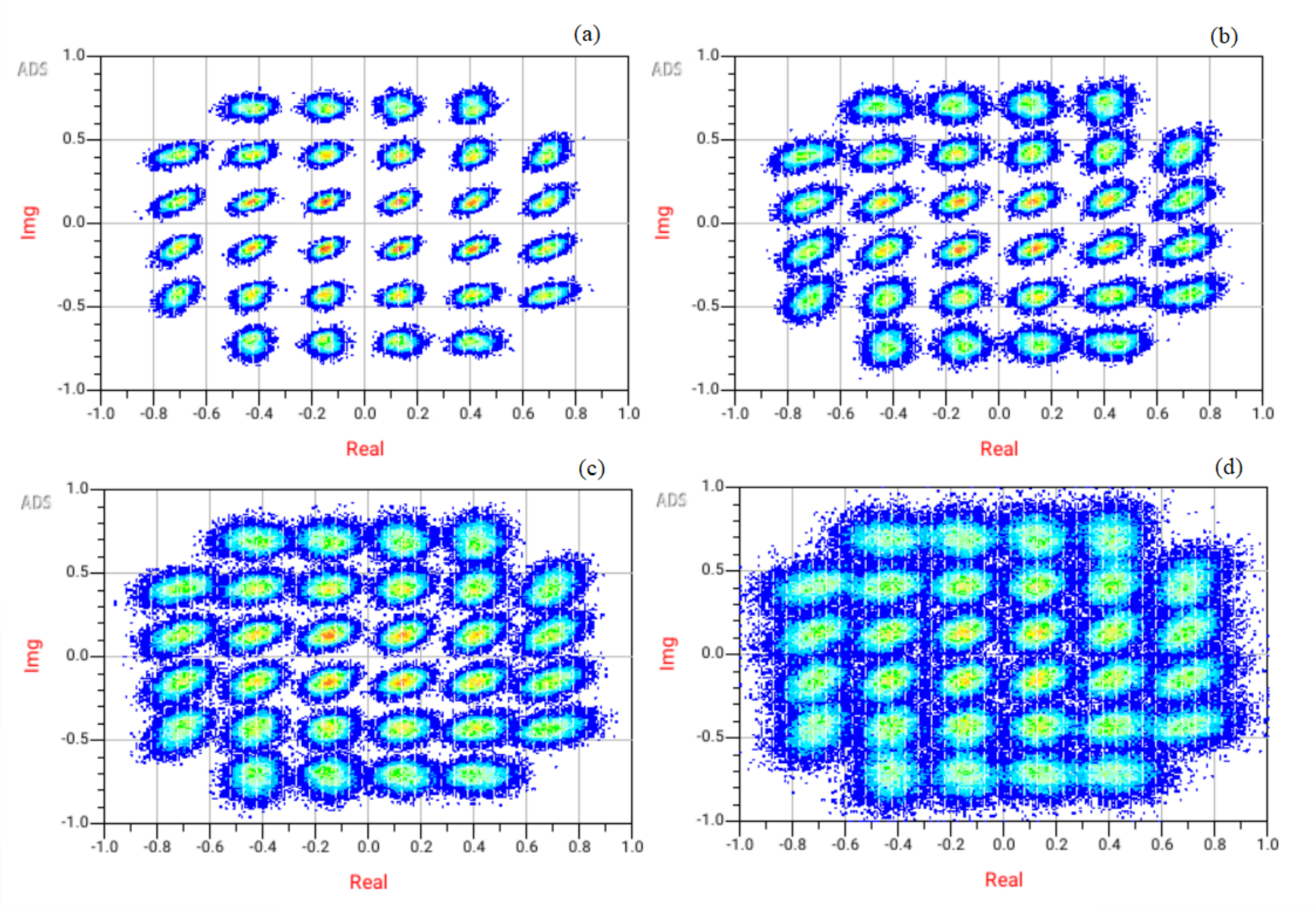
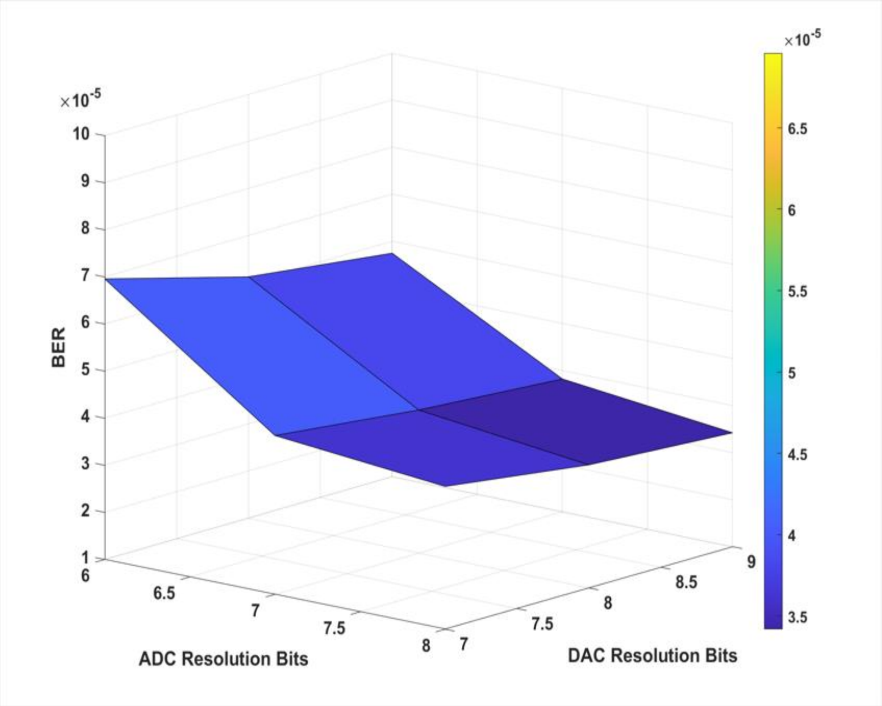
Results of Uniform QAM Modulation (3)

- Constellations of uniform QAM32 at 120 GHz sample rate. (a) Band 7 (b) Band 9 (c) Band 11 (d) Band 13

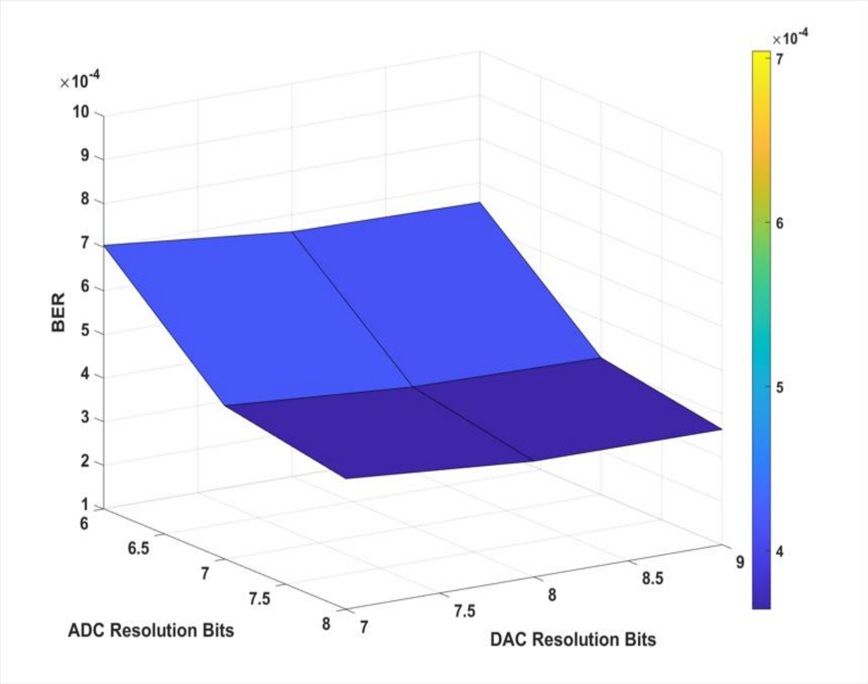


Impact of DAC and ADC Resolutions (1)

- Sweep TX DAC resolution from 7-bit to 9-bit and RX ADC resolution from 6-bit to 8-bit
- Same bit loading as used previously



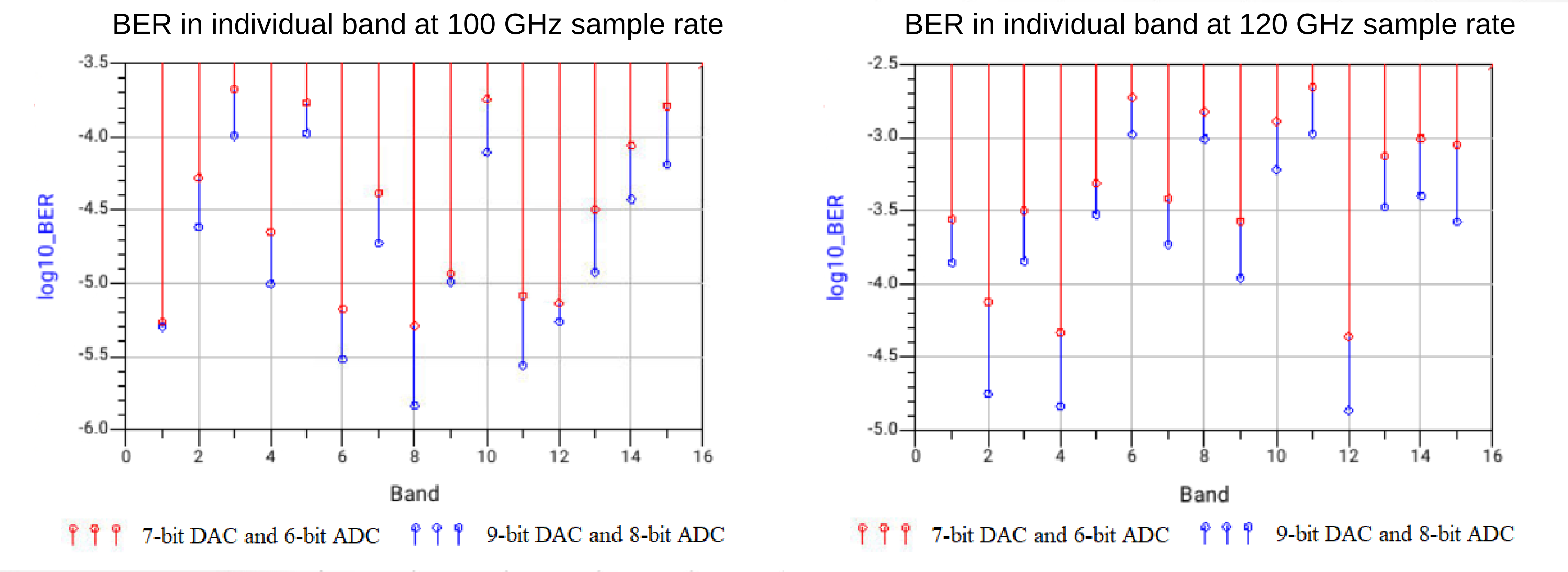
BER vs resolutions at 100 GHz sample rate



BER vs resolutions at 120 GHz sample rate

- BER improves as DAC and ADC resolutions increase

Impact of DAC and ADC Resolutions (2)



- Lower resolution leads to higher BER in all frequency bands

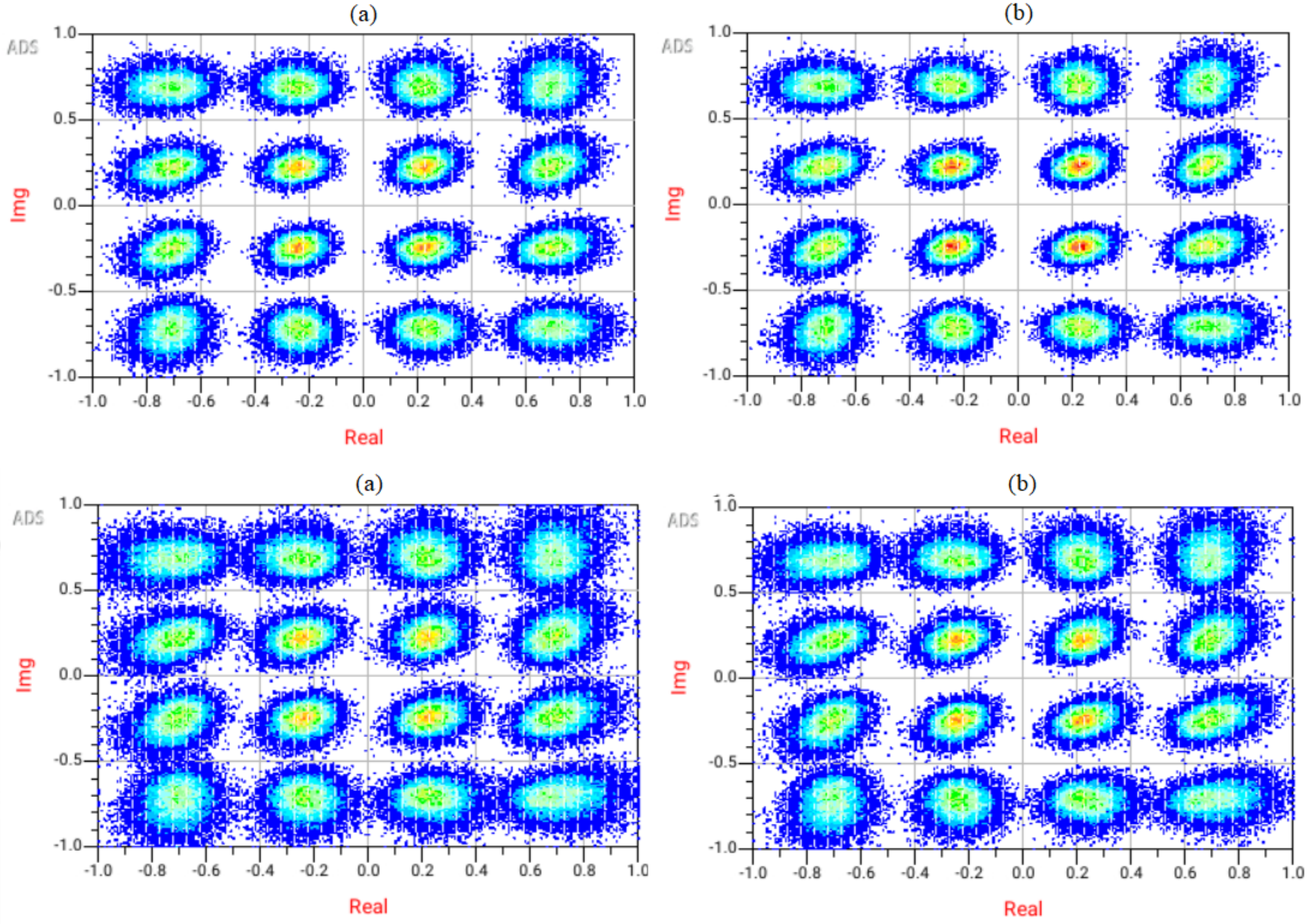
Impact of DAC and ADC Resolutions (3)

(a) 7-bit DAC and 6-bit ADC

(b) 9-bit DAC and 8-bit ADC

Band 13, 100 GHz sample rate

Band 13, 120 GHz sample rate



- QAM signal noise is higher at lower DAC and ADC resolutions, resulting in worse BER

Summary

- DMT working principle is briefly discussed in preparation for the AMI modeling
- IBIS-AMI methodology is extended to enable DMT modeling and simulation
  - TX DLL models bit-to-QAM conversion, IFFT, CP insertion and DAC; The TX AMI_GetWave input is a waveform of binary sequence generated by the simulator, and the output is the waveform of DMT symbols converted from the input bits
  - RX DLL models sample phase detection, ADC, CP removal, FFT, equalization, and QAM-to-bit conversion; RX AMI_GetWave returns recovered bits and QAM constellations
  - During model initialization, TX AMI_Init passes all configuration data required by the RX model such as sample rate, number of sub-channels, bit loading, bit-to-QAM mapping, DMT symbol length and CP length to RX AMI_Init via a proprietary file without the involvement of the simulator
- Examples of DMT with IBIS-AMI modeling are demonstrated
  - Simulated BERs and constellation diagrams are presented and discussed
  - The results show that the system performance is improved by bit loading and higher resolutions of DAC and ADC

Thank you!